Capacitive-Resistive Bioelectrical Signal Measurement Method for Wearable Systems

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Ph.D. Thesis Overview

Capacitive-Resistive Bioelectrical Signal Measurement Method for Wearable Systems

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Abstract

Bioelectrical signals have become an important source of information about the human body and are commonly used in modern hospitals and healthcare facilities during diagnosis, treatment including surgery and recovery by monitoring of patients. Bioelectrical measurement through resistive coupling is traditionally used in such case, but the limitations and effort required to record a satisfactory signal are a big obstacle in the adoption of bioelectrical measurements in daily life. On the other hand, capacitive coupling bioelectrical sensors achieve capacitive coupling between the electrode lead and the user's skin, thereby removing the need for skin preparation and electromechanical contact with the skin, a core property which potentially facilitates high usability and wearability. Though many different models of capacitive coupling bioelectrical sensors have been developed, they all only focus on internal noise sources whereas noise from motion artefacts or nearby electrical appliances has been so far ignored. Because of that, bioelectrical measurements either have less than ideal accuracy or can only be recorded in very limited and artificially controlled environments with some types of bioelectrical signals recording are yet to be reported.

The purpose of this research is to bring the signal robustness expected from traditionally used contact type resistive electrodes and to the potentially more comfortable and practical non contact type capacitive electrodes by reducing the dependency of the bioelectrical information on the contact state between the sensor and the user's skin, approaching this problem from both a internal and external level perspective as well as from system level perspective and developing a hybrid sensor capable of both resistive and capacitive ECG, EMG, EOG and EEG bioelectrical signal measurements.

Development of a novel electric circuit model based on both resistive and capacitive measurement principles as well as all the associated internal noise factors, namely internal thermoelectrical noise, current drift and saturating noise recovery. We extend the sensor model for external noise noise monitoring, namely external electromagnetic noises and motion artifacts and developing a built in dual differential input noise cancelling method. We design and develop a sensor module satisfying the conditions of the developed models introduced. After that, we verify noise and response system properties as well as resistive and capacitive ECG, EOG, EMG and EEG measurements. Because there is no commercial capacitive bioelectrical sensing system, we compare our sensor against traditional wet resistive wet electrodes and obtain similar results. Finally we develop a novel wearable high spatial and temporal resolution and self contained system for EEG measurements in order to minimise noise and demonstrate the full advantages of high wearability and usability that our developed sensors provide. We hope to contribute bringing bioelectrical measurement based prevention and treatment methods that rely on bioelectrical signals in to daily life.

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1. Introduction

Cardioelectrical and myoelectrical signals generated by muscle activity, such as the electrocardiogram(ECG) and electromyogram(EMG), signals that originate from the brain activity, such as electroencephalogram (EEG) signals, and those that originate from the eye movement, such as the electrooculogram (EOG) signals have become an important source of information about the human body and are very important in several fields of medicine.

Wet resistive electrodes such as the Vitrode (Nihonkohden, Japan) or the electrodes used in the G.Tec electrode cap (G.Tec Medical Engineering GMBH, Austria) are used widely to perform these measurements. However, the use of wet electrodes has major drawbacks such as the requirement for skin preparation and the use of conductive gels. Dry resistive electrodes have been developed to increase sensor performance and usability. Dry electrodes involve an active resistive contact with the user's skin, which eliminates the need to use a gel and the problems associated with its use. Skin preparations such as body hair removal and cleaning may be required because constant electromechanical skin contact remains a requirement.

By contrast, noncontact electrodes have been proposed that are capable of achieving capacitive coupling between the electrode lead and the user's skin, thereby removing the need for skin preparation and electromechanical contact with the skin, which facilitates high usability. However, ultra-high input impedances (10^{16}~10^{18} Ω) are required by the design. The ultra-high impedance input is highly susceptible to any electrostatic noise that originates from the surroundings. Therefore, robust shielding, isolation, and current leakage prevention techniques are required to reduce the noise. Furthermore, complex low noise bootstrapping techniques are required to avoid drift due to the bias current from the input. These disadvantages indicate that capacitive electrodes are considerably larger, noisier, and more expensive than conventional electrodes.

Daily life bioelectrical monitoring requires a sensor that gives the potentially high usability of capacitive coupling electrodes while retaining the high sensor performance of conventional electrodes. Our research is focused on the development of a novel sensing method that is capable of recording bioelectrical signals in both a resistive contact mode and a capacitive coupling mode at similar noise levels to commercially available electrodes. Previous studies only considered human body-electrode coupling in their designs, which maximized the input impedance. We also propose the use of noise source coupling in the sensor model. This model allows us to optimize the electrode impedance so that it is sufficiently high to record bioelectrical signals but low enough to reject external electrical noise, as required.

Furthermore, previous studies consisted of only proof-of-concept basic experiments performed at ideal conditions. Noise from real life situations such as motion artifacts or near high-power devices such as electrical motors are still an issue . In order to solve these problems, the sensor must be designed not only to sensitively measure bioelectrical signals but also to sense and subtract external electrostatic noise from the sensor output.

Finally, with the improved usability and wearability of hybrid capacitive-resistive electrodes, the measurement of bioelectrical signals at multiple sources or using high spatial resolution set ups, such as during EEG measurements, comes the problem of recording and analyzing the parallel data in real time. By integrating our hybrid electrodes with a mobile, onboard GPU based data processing system using a modular design, a novel wearable all in one bioelectrical monitoring device that provides simultaneously high usability, portability, versatility and reliability can be achieved.

The aim of this study was to develop a novel electrode that combined the capabilities of both the capacitive and the resistive electrodes by optimizing the electrode input impedance using an original sensor equivalent circuit. Our electrode had to maintain a low noise characteristic that was comparable to commercially available wet electrodes during, ECG, EMG, EEG and EOG measurements. Furthermore we develop a novel hybrid resistive-capacitive electrode using an original sensor based on a circuit model using optimized input impedance for bioelectrical signals while also measuring high frequency noise and removing it from the sensor output. In this study, we focused on a novel extension to our bioelectrical measurement model by actively measuring electrostatic noise and canceling it. Finally, in this study we develop a novel integrated bioelectrical monitoring system combining capacitive bioelectrical measurement and parallel computing technologies.

2. Wearable capacitive bioelectrical sensing through optimal input impedance

2.1 Sensing Theory and Hardware

We designed our hybrid resistive capacitive electrode such that it could function as a resistive contact electrode if electromechanical contact with the skin was not possible. Thus, the electrode collected bioelectrical signals via capacitive coupling if electromechanical contact was not possible. Capacitive sensing measures bioelectrical signals using the AC coupling between the electrode lead and the skin. In our model we may assume the presence of noise sources in the surroundings that are connected via capacitive coupling to the input of the circuit. The impedance between the noise source and the electrode input is usually much higher than the impedance of the electrode-skin interface. Therefore, signals from the electrostatic noise sources may be amplified as well as or better than the bioelectrical signals if the electrode input impedance is excessively high. The effects of noise on the ultra-high impedance input may be strong if the electrode makes recordings using capacitive coupling sensing because input impedance is already very high. Therefore, the input impedance should be set to a minimal value, which is sufficiently high to allow bioelectrical signals to be recorded.

In this study, we developed two form factors for our hybrid electrode. Electrode Type L is a large electrode with a circular 30 mm diameter stainless steel lead, which was based on the Vitrode D design. Type L was designed for low-density sensor networks with maximum comfort in mind. Electrode Type S is a small electrode with two 4 mm^2 cooper leads, which was designed for high-density sensor networks. Type S has the smallest electrode lead area, and hence, it also has the lowest capacitance in the capacitive coupling mode. During the design of the preamplifier circuit board, therefore, we assume a minimal electrode lead area of 8 mm^2. When designing an electrode to record signals with a minimal frequency of 3 Hz that works up to 1 mm from the skin in the capacitive coupling mode, we calculated that a minimal input impedance of approximately 0.85 TΩ is required.

2.2 Parameter Measurements

We measured the frequency responses of our electrodes in the resistive contact mode and the capacitive coupling mode. Our results showed that the experimental cutoff frequency of 2.7 Hz was close to the theoretical cutoff frequency of 2.3 Hz. The results also showed that the hybrid electrode and the model behaved in a very similar manner to a first-order high-pass filter, as predicted by our model. The difference in the cutoff frequency was attributed to the assumptions of our model, which only considered the ideal electronic components of the system.

The noise levels attributable to the electronic sources of the electrode were measured by connecting the inputs of two electrodes. Resistive contact mode measurements were performed by directly shorting the inputs of the two electrodes. Capacitive coupling mode measurements were performed by placing the inputs face to face, separated by only a 1 mm thick insulating rubber layer. The Vitrode and the hybrid electrode in the resistive mode had very similar noise spectrum characteristics in the 10-100 Hz band because they were both resistive contact-type electrodes and they were electrically coupled better with the substrate than the environment. In the 1-10 Hz band, however, our hybrid electrodes had about 1 $\mu V/Hz^{1/2}$ less noise than the Vitrode because our electrode was an active, pre-amplified type of electrode whereas the Vitrode was a passive electrode. The hybrid electrode in the capacitive mode was about 0.3 and 1 $\mu V/Hz^{1/2}$ noisier than the other two cases. However, our new optimal impedance electrode design indicated that the noise levels were at least two times smaller than the weakest bioelectrical signals considered in this study and 4-6 $\mu V/Hz^{1/2}$ smaller than the capacitive coupling electrodes proposed in other studies.

2.3 Static Bioelectrical Signal Measurements

In this experiment we verify if our electrode is capable of recording ECG signals with fidelity by verifying if the component waves of a standard ECG signal are present or not. In this experiment two electrodes following standard ECG electrode placement methods. The subject was wearing a cotton shirt with average thickness of 1mm and the electrodes were placed above the shirt, while the participant seated comfortably on a chair. Ground signal is taken from the back of the right hand of the hand of the participant. From the results we are able to verify that the electrode recorded all the major component waves of the standard ECG waveform.

We also investigate the correlation between the myoelectrical signals such as the EMG data collected from a pair of noncontact electrodes with the EMG data collected simultaneously for a pair of conventional Vitrode disposable wet electrodes. Therefore we investigate the correlation of the data collected by both types of electrodes and verify the nature of the data collected by the developed capacitive coupling electrodes. From the results we can see that the EMG data collected from the Vitrode pair of electrodes overlap most of the data collected by the noncontact electrodes. The calculated correlation coefficient for this dataset was of 0.93, showing that the developed capacitive electrodes are capable of collecting the signals originated from myoelectrical activity and that both the hybrid electrode and vitrode disposable wet electrodes are capable to collect very similar EMG signals.

Eyeball and eyelid movement recordings were made using electrodes in the resistive contact and capacitive coupling modes. Simultaneous recordings with Vitrode F were made for comparative purposes. The Vitrode F electrode pair was positioned as close as possible to our developed electrodes, where the center of each Vitrode electrode was 30 mm from the center of the nearest developed electrode. The Vitrode F electrodes were attached to skin areas that had been cleaned with alcohol to remove any sweat and skin oils, in accordance with the manufacturer's instructions. No skin preparation was required for our hybrid electrode in the resistive or capacitive modes. The calculated correlation coefficient for the data collected from our electrodes in the resistive contact mode and Vitrode F was 0.94, while the correlation coefficient for data collected from our electrodes in the capacitive coupling mode and Vitrode F was 0.92.

Finally The 10-20 Hz band bioelectrical signal recording capacity of our hybrid electrodes was tested by performing alpha and beta band EEG recording experiments. EEG signals were measured while the participant kept their eyes open for 30s when beta waves were predominant, and they were then closed for another 30s when the alpha waves were predominant. Simultaneous readings were also performed using Vitrode electrodes, and the correlation coefficient between the data derived from the hybrid electrode and the Vitrode was calculated. Alpha and beta waves were observed simultaneously in this experiment. The calculated correlation coefficient for the data collected from our electrodes in the resistive contact mode and Vitrode F was 0.86, while the correlation coefficient for the data collected from our electrodes in the capacitive coupling mode and the Vitrode F was 0.85.

3. Wearable System Level Noise Countermeasures

3.1 Sensing Theory and Hardware

Bioelectrical recordings are performed throughout active resistive contact with the skin when the electrodes are capable of electromechanical contact(resistive mode). In the case of poor electromechanical contact conditions, the electrodes measure bioelectrical signals by capacitive coupling with the skin(capacitive mode). The model for our hybrid electrodes contains two built in sensing leads, one for the bioelectrical signals and one for electrostatic noise. Based on our previous studies, we define the input impedance optimal when it is just large enough to allow the sensor electrode to capacitively sense bioelectrical signals. With these settings the sensor input impedance is low enough to reject low frequency capacitive noise signals from the environment.

Based on the proposed electrode model and assuming a maximum 3 mm distance between the electrode and the skin, a circular electrode lead with 38mm diameter and signal input impedance of 1 TΩ was developed. Furthermore, in similar fashion the noise electrode lead is designed. Under these conditions a 1 mm thick ring shaped electrode lead with outer radius of 40 mm is designed. Noise input impedance Rc_N is also set to 1 MΩ, so that only noise signals with frequency above the myoelectrical frequency spectrum are measured. In resistive contact mode the area of the leads has little effect on the input impedance and low input impedance contact are enough to measure bioelectrical signal. Because of that the noise sensing lead is electrically isolated using a thin layer of plastic coating. Without the coating, in resistive contact mode, very similar bioelectrical signals would be collected by both the bioelectrical and noise sensing leads, canceling each other during the differential preamplifier stage at the electrode. A High Pass Filter circuit is also implemented by using traditional circuits in order to eliminate undesirable offset voltages that can appear due to the difference in potential between both electrode sensing leads. Furthermore, back-to-back diodes are also attached to the leads in order to reduce the effects from input bias current. In order to further increase sensor robustness, shielding was implemented by making using of inner layers of the sensor printed circuit board, in which the electronic components as well as most of the circuit pattern is located in the component layer and the sensing leads in the solder layer.

3.2 Noise Measurement

Noise frequency spectrum measurement experiments were performed for both resistive and capacitive modes using this system by placing two electrodes face to face on differential input.

The results show that the maximum noise is of 11 $\mu V/Hz^{1/2}$, which happens in capacitive modes at lower frequencies. As myoelectrical signals are in the order of 100-1000 μV and commonly used signals oscillate in the 30-500 Hz band, the results show that our enhanced hybrid electrodes are reliable enough for myoelectrical measurements.

3.3 Motion Bioelectrical Signal Measurements

In this study we evaluate the performance of our enhanced hybrid electrodes through a two-part experiment. First part is defined by measuring myoelectrical signals when lifting up and letting down various weights and second part is defined by performing robot arm control using myoelectrical signals. The second part of the experiment verifies the operation of the hybrid electrodes near electrical appliances by performing simple robot arm control experiment.

Furthermore, measurement of myoelectrical signals while walking is a fundamental procedure in lower limb to evaluate walking ability accurately in rehabilitation treatments. In this study we evaluate the performance of our enhanced hybrid electrodes during walking by measuring myoelectrical signals from the quadriceps when the participant walks on a treadmill.

The recorded experiment data for the bioelectrical signal measurement under variable load part of the experiment is shown in Figure 7. From the results the correlation coefficient between resistive mode and conventional wet electrode mode was of 0.98. The correlation coefficient between capacitive mode and wet electrode was of 0.92. Therefore the second part of the experiment was performed using only the hybrid electrode in capacitive mode. The arm weight was enough to stimulate the biceps and create a signal strong enough to be used as in a simple trigger algorithm. Moreover, the presence of an electrical motor near the electrodes did not interfere with its functionality and no noise was observed.

Finally, the treadmill experiment results showed constant myoelectrical activity in the quadriceps suggesting continuous load. In particular, during the walking process, the load is the biggest when there is contact of the leg with the floor. From the results we also can observe that the myoelectrical data collected by the enhanced hybrid electrode in both resistive and capacitive mode is mostly overlapping, with a calculated correlation coefficient of 0.76. No visible motion artifacts from leg movements nor electrostatic noise from the treadmill were observed.

4. Wearable High Resolution Real Time Bioelectrical Sensing System

4.1 The importance of electroencephalogram measurements

Brain activity monitoring technologies are fundamental tools in the treatment of neurological disorders, rehabilitation techniques, assistive device interfacing methods and are becomes increasingly important in social and entertainment aspects of wearable computing. Depending on the patient or situation, constant monitoring during daily life is desirable or required. Electroencephalography (EEG) monitoring has been traditionally suggested for daily brain activity monitoring as compared to Magnetic Resonance Imaging (MRI) or Magnetoencephalography (MEG) it is a much cheaper, smaller and versatile solution.

Several EEG technologies are available commercially. Systems such as the BCI2000 and the G.Tec (Guger Technologies, Austria) are used in medical and academic facilities. Such systems are capable of high spatial and temporal resolution. However these products rely on passive resistive electrodes requiring the user to perform skin preparation and lose signal quality with time. Moreover such devices are used as nonwearable computer peripherals, as the headgear and electrodes are wired to a standalone Analog-Digital Converters (ADC) unit which is connected to a host personal computer (PC). This design limits the motion freedom of the user and application scope of the system due to the low portability and usability.

By contrast, systems such as the Epoc headset (Emotiv Systems, Australia) or the Mindwave headset (Neurosky Inc., USA) have been developed targeting entertainment applications. These systems are characterized by having high portability and wearability. However, due to the fixed mechanical design they lack the versatility required for several medical and academic applications. Moreover, the limited onboard processing power limits maximum number of channels a headset can have and an external PC is still required for several applications. Furthermore the lag originated from the wireless connection between the PC and the headset is an issue when real-time processing is required.

From an end-user point of view, brain activity monitoring requires a device with high usability and portability that minimizes the impact on daily life of the end-user. From a professional point of view, a device should provide high spatial and temporal resolution for high responsiveness and signal reliability, it should be strong against noise sources and it also should be flexible enough to provide the opportunity for a wide range of applications over the same platform. A common device that can be used by both professionals and end-users would streamline application development as well as increase data consistence. However such device would also require high usability, portability from the end-user requirements as well as the high versatility and reliability from the professional requirements. In previous researches the authors have developed a hybrid capacitive-resistive electrode for bioelectrical signal capable of signal quality comparable with commercial electrodes achieving high reliability while also achieving high usability as no skin preparation is required and the signal does not degrade with time. Furthermore, while mobile Central Processing Units (CPUs) are not fast enough to perform data collection and frequency analysis simultaneously and in real time of a large number of sensors at high sampling frequencies, the parallel nature of EEG monitoring is compatible with the concepts of parallel processing using Graphic Processing Units(GPUs). Other researchers have already demonstrated the signal processing capabilities and significant performance advantages of GPUs using Compute Unified Device Architecture (CUDA). By integrating our hybrid electrodes with a mobile, onboard GPU based data processing system using a modular design, a novel wearable all in one EEG monitoring device that provides simultaneously high usability, portability, versatility and reliability can be achieved.

In this study we develop a novel integrated EEG monitoring system combining capacitive bioelectrical measurement and parallel computing technologies. A portable high-resolution EEG monitoring headgear composed of up to 112 sensing electrodes and up to 7 reference custom hybrid capacitive-resistive electrodes was developed. In order to record and analyze the massive amount of data from the headgear, a CUDA based wearable processing system was developed providing real-time signal analysis for each sample at 1 kHz sampling rates.

4.2 System composition

119 hybrid electrodes were used to assemble a headset. The headset is composed of two main elements. The first element is a variable link mechanism designed using statistical head anatomical data provided by the Japanese National Institute of Advanced Industrial Science and Technology (AIST). The flexibility provided by using an articulated link mechanism allows the headset to fit on wide range of head geometries. The second element is an elastic net which is attached to the link mechanism. The elastic net is responsible for keeping the link mechanism closed when worn due to the elastic force towards the inside to the headset as well as being the docking place for the electrodes.

The electrodes are placed in a formation fully compatible with the International 10-20 Method for EEG electrode placement. The electrodes are divided in 7 groups of 16 measurement channels and 1 reference for a total of 112 channels and 7 references. The option for having using only one reference electrode for all measurement channels is also available. Each electrode group is connected to a differential input capable 16 channel 16 bit ADC module. All electrodes and modules can be freely added or removed based on the user's need. All modules are connected through USB 3.0 to a dual core Intel Atom Based mother-board with a CUDA capable Nvidia Ion 2 chipset. All the ADC modules, the mother-board and the battery are located in a wearable backpack. The headset weighted 745 g and the backpack weighted 1.80 kg. Data can be stored locally and visualized through an external display or computer.

EEG signals were recorded as a differential signal between a channel electrode and a reference electrode. Signal is amplified, filtered and sampled at 1 kHz at the 16 bit ADC modules. ADC modules simultaneously send the data to the motherboard CPU which stores the data on the memory. Using a different thread, the CPU sends the signal processing instructions and to the GPU.

In this preliminary study we demonstrate the capabilities of wearable GPU based processing for EEG monitoring by performing real time Fast Fourier Transforms (FFT) for all channels in real time on the GPU. Ideally, in our approach, we would perform a FFT based on the Cooley-Tukey algorithm for each channel using a separate GPU thread. However, due to the limitations on number of cores available in the used mobile GPU, we used the minimal recommend 32 CUDA threads, each thread performing the FFT from 4 channels. Because our system had only 112 channels, for code simplicity, we created an additional 16 dummy channels group with duplicated data from real channels to bring the total number of channels to 128. Channel data acquisition and result output is performed using the GPU direct memory access features. Each FFT was performed using the latest 1024 data samples for each channel, after each sampling cycle finished. FFT results are mapped on a human head 3D model for showing EEG signal strength at a chosen frequency at any point of the user's head. The 3D map can be visualized alongside the control graphical user interface for system by plugging in an external monitor or remotely accessing the systems.

4.3 Evaluation experiments

A standard experiments monitoring EEG signals from different areas of the scalp were performed for device testing. The experiment consists in measuring brain activity changes above the frontal lobe due to visual stimuli as well as arithmetic focus. Previous studies have shown that when visual stimulus is strong, such as when doing calculations, it's possible to record strong signals in the beta band (10-20Hz) on the scalp area above the frontal lobe of the human brain. In this experiment we used the beta waves collected from at least 8 electrodes to move a robot arm, as this is the amount of sensor used in other portable wearable EEG monitors. The stimulus was turned on and off every 30 seconds during the total experiment time of 600 seconds.

In order to evaluate the impact of the use of the GPU, both experiments were performed with and without using the CUDA features described in Section 2.2. The experiments were performed with 6 participants, each experiment was performed 10 times.

When experiments were executed with the CUDA features described in Section 2.2, the system was able to record data from all 112 channels at 1 kHz and perform FFTs for all channels after each sampling without delay or data loss. On the other hand, without using the CUDA features, thus allocating all the stress entirely on the CPU, the system took up to 400 ms to finish the FFTs for all channels and was unable to keep up with the 1 kHz sampling rate.

As for EEG measurement, the developed system was capable to record the data on all participants as expected from the results of previous researches. All electrodes showed strong signals when the calculation was done whereas a weak signal was recorded when in relaxation. All participants controlled the robot arm with a minimal success rate of 75%, which is around 10% more than on other researchs.

5. Discussion

EOG and EEG signals are used extensively for sleep disorder diagnosis and treatment, assistive device control, and neurorehabilitation. Furthermore, ECG measurements done by a Holter Monitor for long periods of time are frequently used to diagnose cardiac diseases or measure cardiac stress under physical exercises and EMG measurements are used to interface with exoskeletons such as the HAL robot suit or prosthetic limbs. the effectiveness of some of these medical applications is highly dependent on the frequency at which the patient uses the equipment. One of the main obstacles in the spread of these technologies is the difficulty of placing electrodes and performing measurements during daily life because of the requirements for skin preparation and the electromechanical contact problems associated with conventional electrodes. From a usability perspective, our electrodes are easier to use than any commercially available electrodes. Skin preparation is unnecessary and our electrodes can even measure bioelectrical signals in covered body areas were electromechanical contact is impossible.

One of the key aspects and the breakthrough point of this paper is the implementation of the novel dual signal lead system with a differential preamplifier unit built in the electrode. Comparing to previous studies from other groups, this breakthrough point is better design choice than applying an analog or digital Low Pass Filter during signal conditioning because it removes a significant amount of noise before the electrical signal enters our system, avoiding problems caused by the limits on operational amplifiers power supply as well as signal distortion and lag from the filters.

The experimental results support our electrode impedance optimization method and our optimal model in terms of its noise and frequency utility. The optimization results showed that the noise levels were 4-6μV/Hz$^{1/2}$ lower than those reported by other studies. Our optimized design allowed us to develop an 8 mm^2 capacitive coupling electrode, which was four times smaller than electrodes developed in other studies. This smaller size allowed us to develop the first portable 128-channel high-resolution EEG headset based on capacitive coupling electrodes. The frequency response results were very close to the theoretical values; however, the observed difference suggested that the resulting input impedance in the actual electrode is slightly lower than the target value. This was not a problem for the applications described in this paper; however, some commercial and medical situations require very high levels of reliability or industrial standard definitions, so a full understanding of the electrode impedance may be required. An enhanced model that includes resistive and capacitive elements using additional board components and board design features, and different materials, may be introduced in future works.

The observed correlation coefficients for the EOG experiments presented in Section 4.3 were all above 0.90. However, the correlation coefficients in the EEG experiments were between 0.84 and 0.90. The EEG readings had lower correlation coefficients because they were 10-100 times weaker than the EOG signals. Weaker signals had a larger effect on the random thermal noise, which reduced the correlation between the two different readings. Another factor was the distance between the electrodes. Previous studies have shown that a 30-mm distance between the centers of the two electrodes during simultaneous recordings was sufficient to produce different signals and a lower correlation.

With our hybrid electrodes removed the need of skin preparation, the wearability of the system was further increased by using a novel mechanism the allows the placement of over a hundred EEG electrodes over the users scalp simultaneously, thus reducing the time for wearing our 119 electrode system to up to 5 minutes, similar to the time required for 1-16 electrode systems. Quick and easy electrode placement is fundamental for daily life usage, as it gives the user time to perform other activities while also it does not require specialized staff or training for correctly wearing the system. Furthermore, the lack of conductive gel and the problems associated with it such as signal degradation over time are completely avoided rendering battery capacity the only limiting factor for long continuous monitoring sessions. Using hybrid capacitive-resistive electrodes provided a high usability required by end users while also increasing the reliability of the system without reducing the spatial resolution of the sensor network.

The experiments have shown that our GPU based signal processing algorithm is powerful enough to perform FFTs for each channel after each sampling is finished, at 1 kHz sampling rate. While sampling at 1 kHz is a common practice, performing FFTs for each sampling at this rate is excessive considering the relatively low frequency EEG bioelectrical signals oscillate. However in this study, by showing that our system can perform heavy calculations at very fast rates, we show that our system perform in real time under heavy load by using algorithms optimized for parallel processing. On a realistic application scenario we can reduce the FFT execution and use the GPU processing power for other parallelizable tasks, such as neural networks[17]. Offloading signal processing to the GPU using CUDA not only allowed us to perform frequency analysis at real time but also freed the CPU for writing data to the hard-disk as well as displaying a fully interactive GUI with a 3D map of the EEG signals over the scalp. The high speed data processing allowed us to support a high spatial and temporal resolution which increase the reliability of the signal while leaving the CPU free for user interaction contributing in increasing the usability of the system. Furthermore, using a mobile GPU allowed us to have all these advantages in a wearable package, achieving a system with high portability and removed the need to have an external host PC, creating an all-in-one integrated system.

The data transfer between the electrodes and the GPU equipped mother-board was performed by seven 16-channel modules. This modular design allows users to add or remove at will. Taking advantage of this design professional users can perform experiments and development using high-density sensor networks, whereas when supplying the EEG monitoring system for the end user they can easily reduce hardware and optimize the system for the target application while still maintaining system consistence, thus reducing costs but offering a high application flexibility. In this study our system was a proof-of-concept prototype, thus also containing not optimized off-the-shelf parts, such as the motherboard containing the GPU. With the popularization of GPGPU capable System on Chip devices further increasing the miniaturization and increasing power efficiency can be achieved in the near future.

6. Conclusion

In this study we developed a novel electrode that combined the capabilities of both the capacitive and the resistive electrodes by optimizing the electrode input impedance using an original sensor equivalent circuit. Our electrode had to maintain a low noise characteristic that was comparable to commercially available wet electrodes during, ECG, EMG, EEG and EOG measurements. Furthermore we developed a novel hybrid resistive-capacitive electrode using an original sensor based on a circuit model using optimized input impedance for bioelectrical signals while also measuring high frequency noise and removing it from the sensor output. We focused on a novel extension to our bioelectrical measurement model by actively measuring electrostatic noise and countering it. Finally we developed a novel integrated bioelectrical monitoring system combining capacitive bioelectrical measurement and parallel computing technologies for real time measurements.

In future works we plan to expand the development of the capacitive-resistive hybrid bioelectrical method in the realm of non-wearable devices as well as integrating all the technologies described in this study in the construction of a self-contained rehabilitation platform. Furthermore we plan to exploit the modularity of the systems described for wearable GPGPU processing and expand the application beyond bioelectrical measurement systems.